Numerical Weather Prediction

Ozone Data Assimilation: Preliminary System

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David Jackson and Roger Saunders

email: nwp_publications@metoffice.com

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Abstract

The ultimate goal of this work is to demonstrate that assimilating ozone will have a positive impact on numerical forecasts. This may happen via improved assimilation of satellite radiances, improved radiative heating rates, and impacts on upper tropospheric / lower stratospheric winds through the coupling between ozone and dynamics. Ozone assimilation should also lead to improved ozone and surface UV forecasts. In this paper, current work to include ozone as an analysis variable in the Met Office 3D-Var scheme is described. A simplified system has been developed in which ozone is assimilated using High Resolution Infrared Sounder (HIRS) radiances. The background ozone is calculated using the Unified Model (UM) tracer transport equation, and the analysed ozone is assumed to be uncorrelated with other analysis variables.

10 day trials were run. In the control trial ozone was advected by the UM winds, but no ozone data were assimilated; in the test trial, the ozone assimilation was switched on. The trial results show an improvement in model total ozone compared to Global Ozone Monitoring Experiment (GOME) data when the ozone assimilation scheme is switched on. A comparison with Total Ozone Mapping Spectrometer (TOMS) data also shows an improvement, except at southern mid and high latitudes. This may be because TOMS is less accurate than GOME in this region. Furthermore, model ozone profiles in the upper troposphere and lower stratosphere are generally in better agreement with observations from the Halogen Occultation Experiment (HALOE) when the ozone assimilation is switched on. A validation of temperature profiles against sonde data shows that the ozone assimilation has a neutral impact on analysed and forecast temperature, compared to another trial run that mimics the operational stratospheric model.

The trial results indicate that the ozone assimilation scheme is performing satisfactorily, and therefore the way is clear to move on and further develop the scheme. Planned improvements include: use of improved ozone background error covariances; use of data from the Solar BackScatter Ultraviolet radiometer (SBUV); inclusion of a chemical ozone parametrization in the UM; use of UM New Dynamics (UM) (the current trials use the old UM dynamical core); inclusion of a feedback between analysed ozone and the model radiation scheme; including correlations between ozone and other analysed variables.

1 Introduction

There is now an abundance of daily observations of atmospheric ozone. A few are made by ozonesondes and ground-based spectrophotometers, but the bulk are made via remote sensing. Global total ozone fields are available both from the Total Ozone Mapping Spectrometer (TOMS) and the Global Ozone Monitoring Experiment (GOME). High Resolution Infrared Sounder (HIRS) observations provide information on upper tropospheric / lower stratospheric ozone, whilst stratospheric ozone profiles can be inferred from Solar Backscatter Ultraviolet radiometer (SBUV) observations. All these data are available daily in near real time and thus can be used to provide operational ozone analyses. For example, the European Centre for Medium Range Weather Forecasts (ECMWF) operationally assimilate ozone using 4D-Var from GOME and SBUV observations, and are planning to add HIRS radiances to this analysis (A. Dethof, pers. comm.), whilst the Royal Dutch Meteorological Institute (KNMI) use a Kalman filter technique to produce daily total ozone fields from GOME data (Eskes et al, 1999; Jeuken et al, 1999). Furthermore, Meteo-France assimilate total ozone fields from the TIROS Operational Vertical Sounder (TOVS) (Peuch et al, 1999) and the Data Assimilation Office (DAO) assimilate SBUV and TOMS data using an off-line ozone transport model and a Physical-space Statistical Analysis Scheme (PSAS) (Stajner et al, 2000).

There are a number of reasons why adding ozone to the Met Office's 3D-Var assimilation scheme (Lorenc et al, 2000) could have a positive impact on numerical weather prediction (NWP). These include: impact on wind fields through correlations between ozone and potential vorticity and other dynamic variables (though 4D-Var will provide a more optimal impact on wind fields); improved assimilation of satellite radiances; improved radiative heating; improved predictions of UV radiation.

This note describes initial attempts to set up a simplified ozone assimilation system, with the aim of demonstrating that it works adequately (called 'Stage 1'). Later work (Stage 2) will involve refining the system to bring it close to the point where it may be considered for operational implementation. The Stage 1 changes are documented in Section 2 and results from data assimilation trials using them appear in Section 3. Conclusions and an outline of the planned Stage 2 changes appear in Section 4.

2 Ozone Assimilation in 3D-Var

In Stage 1 of the project, ozone is assimilated using the Met Office's current operational stratosphere - troposphere data assimilation system (Swinbank et al, 2002), which is based on a 40 level version of the Unified Model (UM), with a top level near 0.1 hPa and a horizontal resolution of 2.5^o latitude x 3.75^o longitude. The background ozone field required for the assimilation is calculated using a tracer transport equation within the UM. It may also be desirable to include a parametrization of the chemical production and loss of stratospheric ozone (following eg Cariolle and Deque, 1986), but for simplicity this is omitted in Stage 1. Currently, the model radiation scheme uses climatological ozone rather than assimilated ozone. Later on (towards the end of Stage 2), when the performance of the ozone assimilation scheme is deemed to be acceptable, this will be changed to allow the investigation of the interaction between assimilated ozone and radiative heating.

Further details of the ozone data used, the 3D-Var code changes made, and the ozone background error covariances selected appear in the remainder of this section. Technical details pertaining to these changes appear in the Appendix.

2.1 Data Used

The Stage 1 system assimilates ozone only from brightness temperatures from the High Resolution Infrared Radiation Sounder (HIRS). A persuasive reason for following this approach is that the the forward model code is already available and thus the ozone assimilation system can be set up quicker than if data from other instruments that are not presently included in the Met Office system (eg SBUV, TOMS) are used.

Brightness temperatures from HIRS channel 9 are strongly sensitive to ozone mixing ratio, and in addition many other temperature sounding channels are slightly influenced by ozone changes. This is demonstrated by Figure 1, which shows the response of HIRS brightness temperatures to a 10 % reduction in ozone mixing ratio. Currently, HIRS channel 9 is not used operationally since the model ozone is fixed. However, with the introduction of ozone assimilation, these brightness temperatures can be used to influence the model background ozone field. In addition, assuming the assimilation of ozone is realistic, the perturbations due to ozone in the other sensitive HIRS channels will be accounted for, thus improving their accuracy for retrieving temperature and water vapour fields.

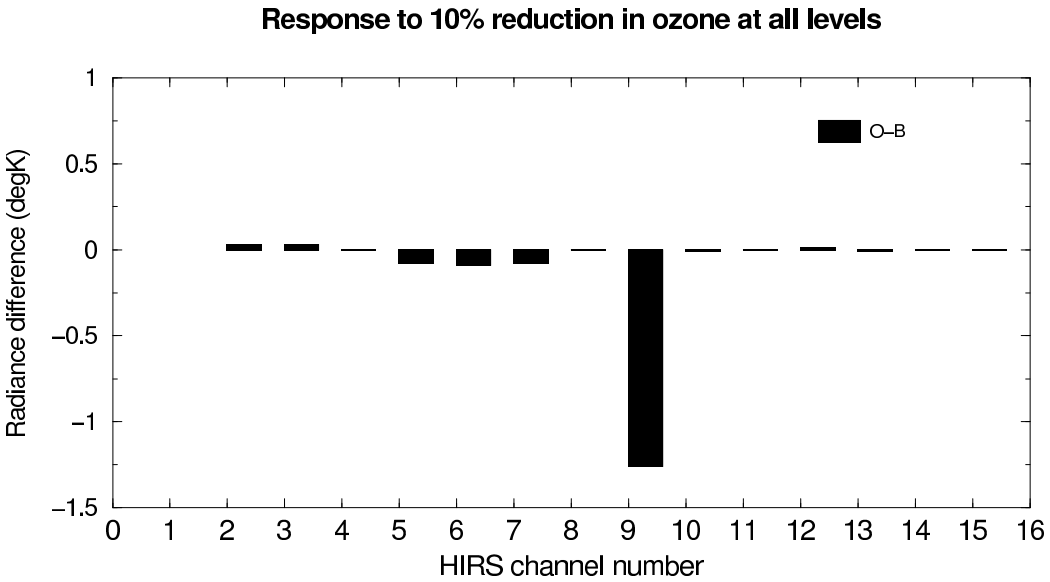

Figure 1: Response of HIRS brightness temperature to a 10 % reduction in ozone at all levels

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HIRS channel 9 data from NOAA-16 are used in the trials (data from NOAA-15 are too unreliable and are omitted; later, when they become available, data from NOAA-17 will also be used). Operational bias corrections are available, but these are not suitable for the trials since HIRS channel 9 is not used in the operational system, and because the trials use a more recent version of the ATOVS [1] forward model (RTTOV-6 instead of RTTOV-5, which is used operationally). Accordingly, new ATOVS bias corrections had to be calculated prior to running the trials. The bias corrections were calculated from statistics generated by running a week-long assimilation run which included HIRS 9 data and the RTTOV-6 forward model in the OPS step, but which excluded all ATOVS channels from the 3D-Var assimilation.

[1] the Advanced TIROS Operational Vertical Sounder (ATOVS) comprises of three instruments, including HIRS

2.2 3D-Var Changes

The 3D-Var code was modified to include ozone as a control variable. This involved modifications to include ozone in the calculation of the background and ATOVS radiance observation penalties (and hence the total penalty). Further changes were added to include ozone in the reconfiguration of the UM dump to the linearised state (LS) (immediately prior to the assimilation) and in the adding of perturbation forecast (PF) increments to the UM dump (immediately after the assimilation).

An important part of the 3D-Var scheme is the transforms of the control variables that are made in order to eliminate the unwieldy background error covariance from the calculation of the cost function, and to make this calculation much more computationally efficient (Lorenc et al, 2000). To this end, the ozone background error covariance matrix has been filtered, to allow for different scales in the horizontal, and has been transformed into empirical modes in the vertical, using zonal and seasonal average statistics. The vertical covariances are calculated from data supplied by ECMWF (see below), whilst the horizontal covariances are isotropic and Gaussian, with a length scale of 600 km. The latter formulation follows the approach of a recent study in which ozone data from the Microwave Limb Sounder (MLS) and the Global Ozone Monitoring Experiment (GOME) were assimilated (Struthers et al, 2002). Note that the data from ECMWF do not allow for any latitudinal or seasonal variation in the background errors, at least at this stage.

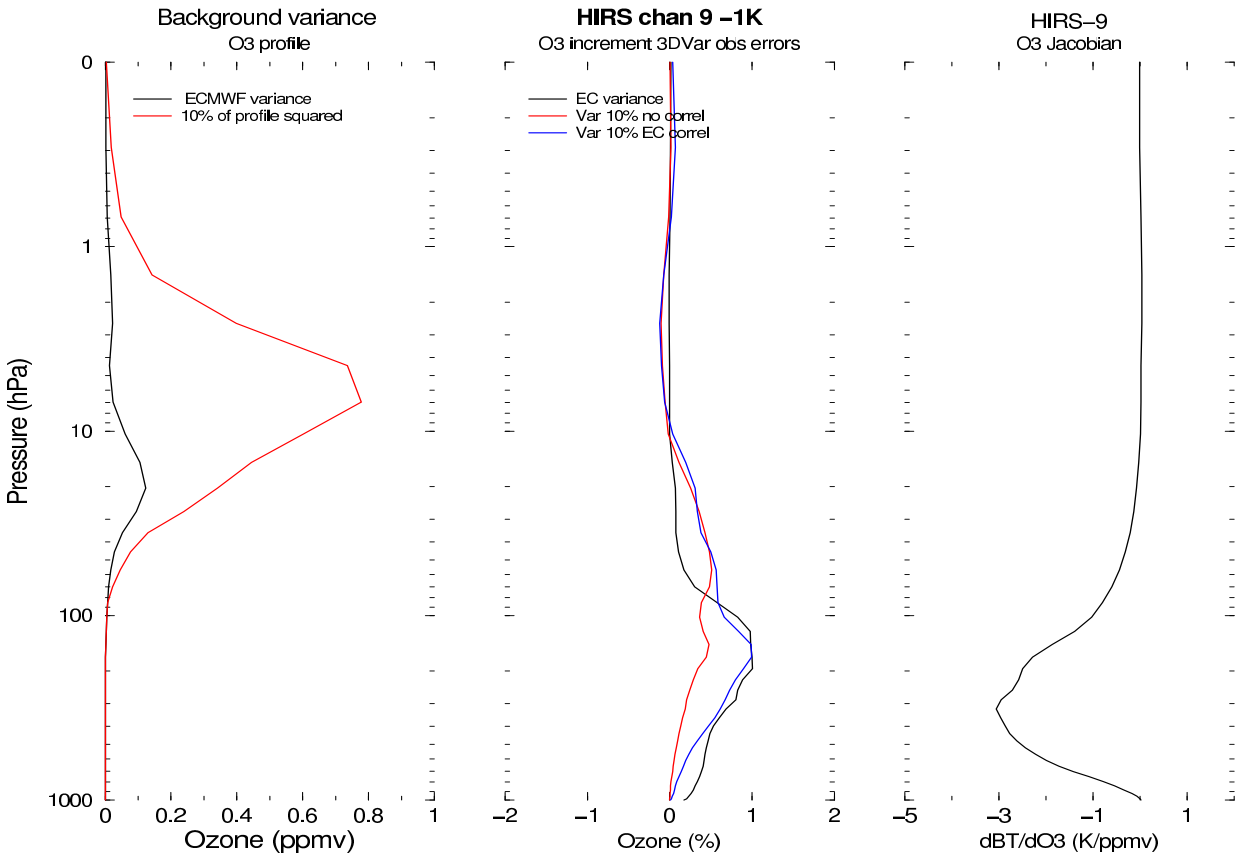

Figure 2: Background error standard deviations under test (left panel); percentage change in ozone following 1 K change in HIRS channel 9 brightness temperature (centre panel); ozone Jacobian for HIRS channel 9 (right panel)

The 3D-Var scheme also includes the option to perform a physical transform of an

analysis variable to another, related, variable which has negligible (or, at least, small) correlations with the other analysis variables. As already mentioned, this transform is done to eliminate the background error covariance matrix from the calculation of the cost function and would be necessary if the correlation between ozone and upper troposphere / lower stratosphere winds was represented. However, here, for simplicity, it is assumed that ozone is not correlated with any other analysis variable and thus no such physical transform is needed. Such changes will be considered in Stage 2 (see Section 4).

2.3 Background Error Covariances

Background error covariances used in the Met Office assimilation system are calculated using the so-called 'NMC Method' (Parrish and Derber, 1992). Once the ozone assimilation scheme is up and running, it is planned to generate error covariances in this way using statistics from assimilation trials. However, to start with, one must select an appropriate background error covariance matrix from another source. A number of possible representations were considered, and the appropriateness of each was tested using a 1D-Var version of the HIRS radiance assimilation Further details of these 1D-Var experiments appear in Saunders (2001). Three candidates were tested: 1) background errors provided by ECMWF and calculated from perturbed analyses; 2) a simplified model with no vertical correlations and a variance that is the square of 10 % of the background ozone mixing ratio (similar to that used by Struthers et al, 2002); 3) a hybrid solution that uses the vertical correlations from 1) and variances from 2). We examined the ozone increments for these three matrices that resulted when the HIRS channel 9 brightness temperature was reduced by 1 K. Results are shown in Figure 2. The Jacobian indicates the sensitivity of channel 9 to changes in ozone and, encouragingly, all three matrices gave rise to ozone changes near the peak of Jacobian. However, matrices 2) and 3) also produced ozone changes far away from this peak, between 10 and 1 hPa, which is not desirable. For this reason, our initial trials shall use matrix 1). Note that in the time between the completion of these experiments and the start of the assimilation trials updated error covariances were received from ECMWF. These updated values are used in the trials described in Section 3.

3 Trial Results

Two data assimilation trials were run for 10 days starting from 12Z on 26th March 2001. All initial conditions were taken from the operational Met Office stratospheric analysis from that time, with the exception of the ozone field, which used March monthly mean values from the climatology of Li and Shine (1995).

Three runs were made. The control run is similar to the existing Met Office operational stratospheric system, except that HIRS channel 9 data, the RTTOV6 ATOVS forward model, and new ATOVS bias corrections are used (see also Section 2.1). Data from surface, sonde and aircraft reports, satellite cloud track winds and other ATOVS channels are also included. The ozone is advected as a passive tracer by the UM but is not assimilated. The ozone mixing ratios used in the ATOVS forward model are taken from a global mean reference climatology, not from this UM background field.

This set-up of the control run was chosen so that any impacts of introducing ozone assimilation in the test run can be clearly demonstrated. However, HIRS channel 9 data are not used operationally, since if they are included without ozone assimilation this may degrade the temperature analysis. Accordingly, a further run was made which excludes HIRS channel 9 data and ozone assimilation. Results from this are discussed in Section

3.2

The test run is similar to the control run except that ozone is assimilated. The UM background field is used in the ATOVS forward model calculations, and then the analysis increment is added to the background value.

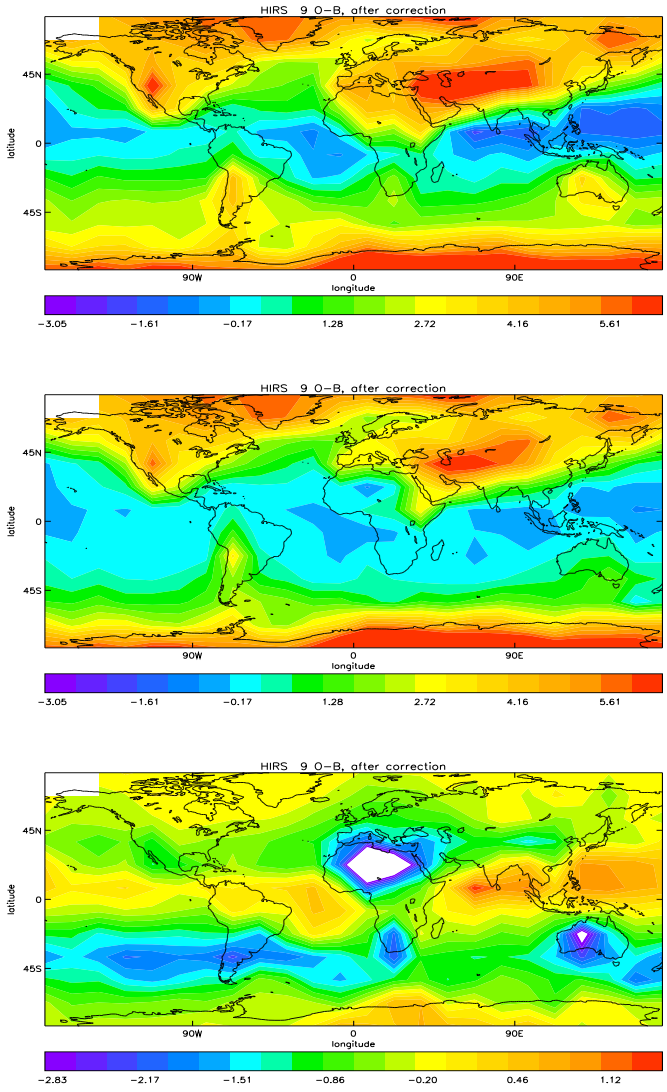

Figure 3: O-B for HIRS channel 9 brightness temperatures: control run (top panel); test run (middle panel); test - control run (bottom panel). Units: K

The differences between observed and background and analysed HIRS channel 9 brightness temperatures (so-called O-B and O-A, respectively) are one indicator of the quality of the analyses. These both decrease when the ozone assimilation is switched on. Figure 3 shows that the introduction of ozone assimilation reduces the large positive O-B biases over the Sahara, Australia, western USA, central Asia and the south Pacific. In addition, negative biases are reduced over the Indian ocean and the Pacific warm pool. For O-A differences, both mean and RMS values for HIRS channel 9 brightness temperatures are around 3.0 K in the control run. However, these differences are reduced considerably when ozone assimilation is switched on (see Figure 4). The left panel shows that in the test run the mean O-A difference is around -0.5 K throughout the run. Furthermore, the iterations through 3D-Var act to reduce the sometimes large O-A errors that are seen for the zeroth iteration (black line), and RMS O-A differences (right panel) for the final

iteration in each cycle are around 0.5 K, which is about half those for the zeroth iteration (note that no errors are shown for 31st March and 1st April, because on these dates ATOVS data were not stored in the operational database (for technical reasons)).

Figure 5 shows the ozone analysis increment from the test run at 50 and 200 hPa. It can be seen that the largest increments are over the ocean and that over the land the increments are zero or close to zero. This is because the HIRS channel 9 data over land are not used in the assimilation. Furthermore, these data are not used in cloudy conditions, and so analysis increments over cloudy regions such as the Pacific warm pool are also small or zero. The increments at 50 hPa are typically around 4 times as large as those at 200 hPa, but, since mean ozone mixing ratios at 200 hPa are over 10 times smaller than at 50 hPa, this means that the percentage change in ozone at 50 hPa is actually under half that at 200 hPa. This is consistent with the middle panel of Figure 2. Furthermore, the ozone increment at 1000 and 10 hPa is negligible, which also is consistent with Figure 2 and which indicates that the impact of HIRS 9 data on the ozone profile in the 3D-Var trials follows the pattern indicated in the 1D-Var tests.

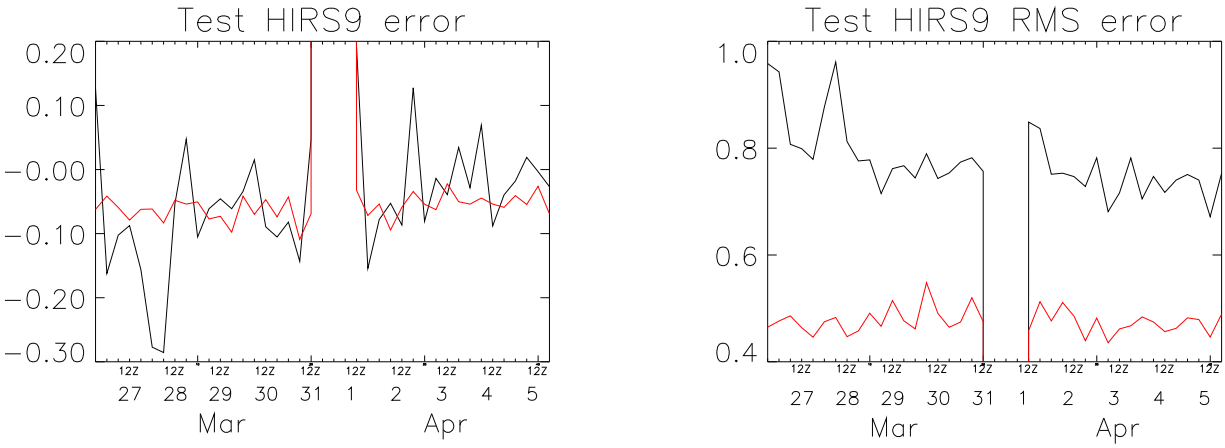

Figure 4: Test run: mean (left panel) and RMS (right panel) O-A differences for HIRS channel 9 brightness temperatures for the zeroth (black) and final (red) iterations of the 3D-Var scheme (NB: no HIRS data are available between 12Z on 31st March and 12Z on 1st April). Units: K

3.1 Verification of Ozone against Correlative Measurements

The results shown in Figures 3 and 4 indicate an improvement in the analysis when ozone assimilation is switched on. This is not surprising. In the control run the background and analysed values of HIRS channel 9 brightness temperature were calculated using a fixed, global mean reference ozone profile supplied by the RTTOV package, rather than the UM ozone field, as is the case with the test run (this is because, at this stage, it is not practical to make such calculations using the UM ozone field if the ozone assimilation option is not selected). Therefore, the results from Figures 3 and 4 only really indicate that the ozone assimilation system is working adequately and without gross errors.

For a better assessment of the improvement (if any) in the model ozone analysis via ozone assimilation it is necessary to make a comparison with correlative measurements. Thus, the UM ozone fields from the control run (which is equivalent to background field since no ozone data are assimilated) and the test run are compared with data from 3 sources: Assimilated GOME total ozone fields, TOMS total ozone observations, and Halogen Occultation Experiment (HALOE) ozone profiles.

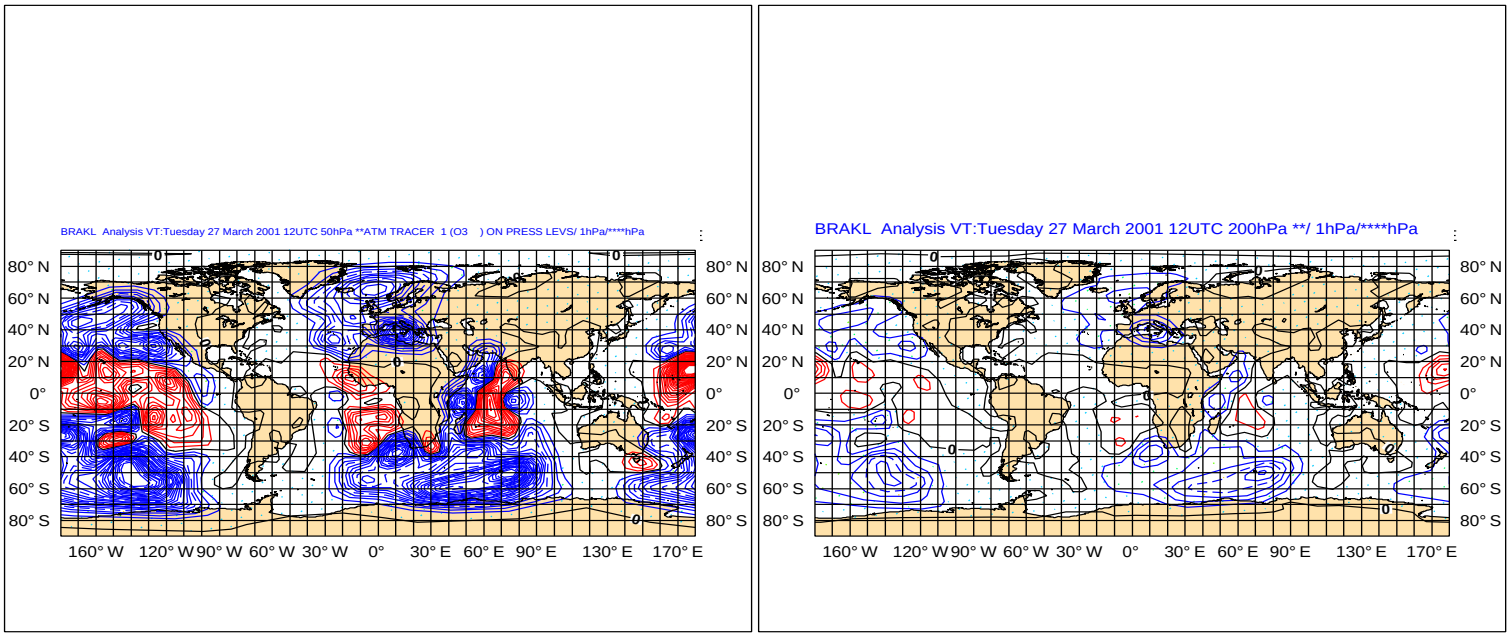

Figure 5: Ozone analysis increments at 12Z for the test run, averaged over the 10 days of the run: 50 hPa (left panel) and 200 hPa (right panel). Contour interval is 0.002 ppmm.

The GOME (Burrows et al, 1999) dataset has been produced by assimilating GOME total ozone data using a tracer transport model (Eskes et al, 1999; Jeuken et al, 1999). The output is on a 1.25^o x 1.25^o grid and is available from KNMI. The TOMS (Heath et al, 1975) data are on the same resolution grid and are available from the NASA Goddard Space Flight Center. The TOMS data are not assimilated, and hence there are a number of points where there are no data, chiefly at high latitudes and also at some points in the tropics where the zonal distance between successive orbits exceeds the swath width. The HALOE data is available from the NASA Langley Research Center. HALOE (Russell et al, 1993) is a solar occultation instrument, and thus benefits from high vertical resolution and self-calibration, but a drawback is that it can only observe at two latitudes per day (one each for sunrise and sunset events). HALOE ozone profiles are available between the upper troposphere and the mesosphere.

3.1.1 Verification against GOME and TOMS Total Ozone

Figure 6 shows the model and GOME total ozone fields for 12Z on 5th April 2001. Both control and test runs adequately represent most of the gross features of the GOME field, such as the steep gradient in the northern mid latitudes. The small-scale structure seen in the GOME field, particularly in the tropics, is however not well represented by the model, probably because the model resolution is coarser than the GOME data resolution.

The difference between control and test run fields is largest in the southern hemisphere. This is because no HIRS 9 data are used over land and, since the land area is smaller in the southern hemisphere than in the northern, there will be a smaller number of points with a non-zero ozone increment. This is seen clearly in Figure 5. Figure 5 also shows that the localised ozone increments are largest in the southern mid and high latitudes, possibly indicating that the ozone initial conditions are less accurate than at other latitudes. Including ozone assimilation reduces total ozone at almost all points in the southern hemisphere, and this reduces the negative O-A bias at high southern latitudes. In southern mid latitudes the effect is more to change a small negative O-A bias to a small positive O-A bias (Figure 6).

The behaviour of the model total ozone error compared to GOME measurements

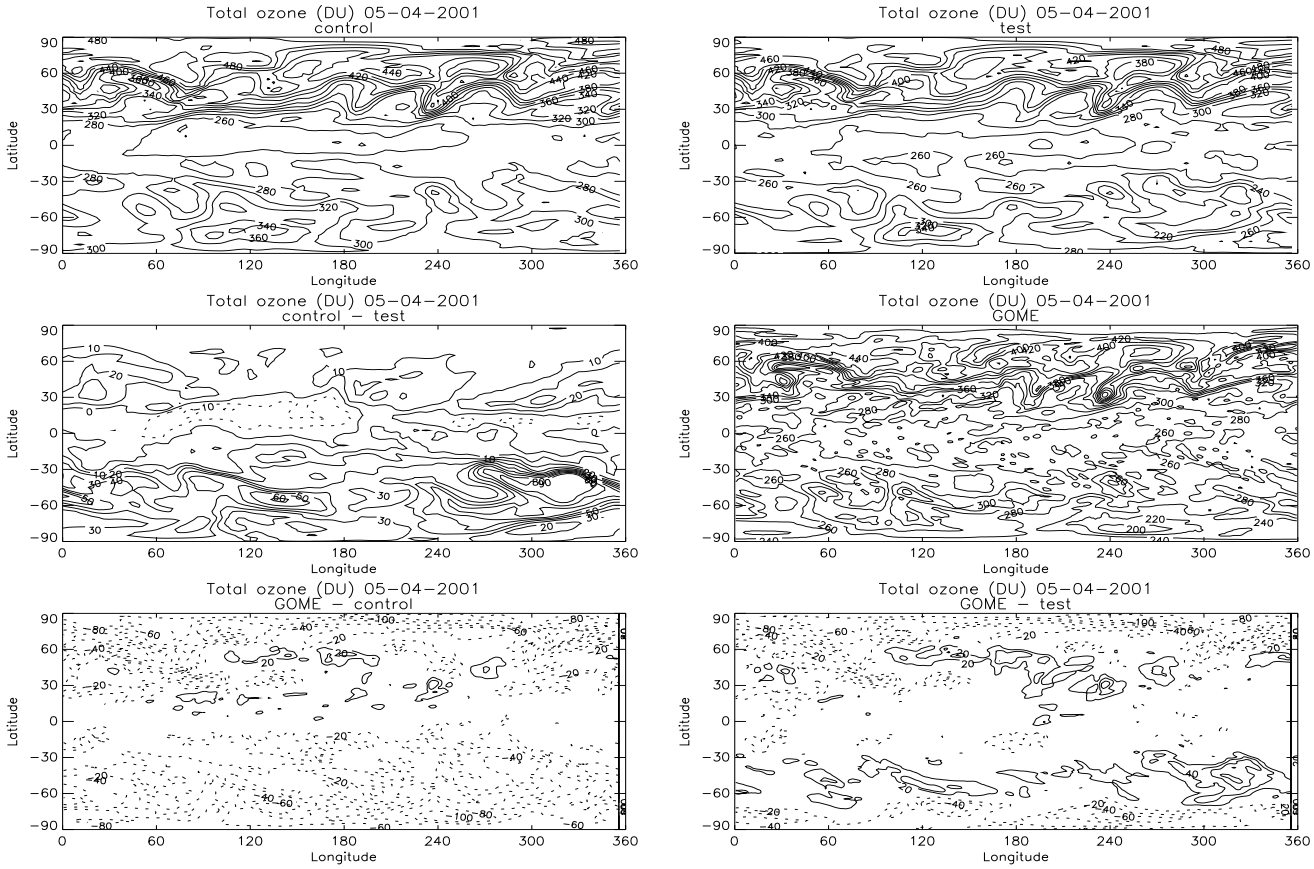

Figure 6: Total ozone for 12Z on 5th April 2001. Control run (top left panel); test run (top right panel); control - test run (middle left panel); GOME field (middle right panel); GOME - control (bottom left panel); GOME - test (bottom right panel). Units: DU

is better summarised in Figure 7, which shows mean and RMS errors for the northern and southern mid to high latitudes and the tropics. The impact of including ozone assimilation is beneficial, with the positive bias in the analysis and its RMS error reduced in all three regions. The impact is greatest in the southern hemisphere, where the control run bias is around 45 DU smaller than the test run bias towards the end of the model run. The differences between the runs seem to increase with time, and thus it may be that 10 days is not long enough for the assimilation to have properly 'spun up' and for the errors to become more stable in time (although an Observation System Simulation Experiment carried out with this scheme to investigate the impact of Stratospheric Wind Interferometer for Transport Studies (SWIFT) observations showed that the spin up time for ozone may only be 2-3 days). It would be interesting to extend the trials for another few weeks to investigate the evolution of the model errors.

Figure 8 shows the corresponding model total ozone errors with respect to TOMS measurements. Results are quite similar to Figure 7 for the tropics and northern hemisphere, with the exception that both mean and RMS errors are around 5-10 DU smaller in the latter case. However, much more striking differences are seen in the southern hemisphere. Instead of a reduction of a large positive bias to almost zero (as shown in Figure 7), a small initial negative bias quickly switches to a positive bias that increases with time to the end of the run. In addition, after around 4 days of the run, the RMS error for the test run exceeds that of the control run.

The different error behaviour in Figures 7 and 8 of course implies differences in the

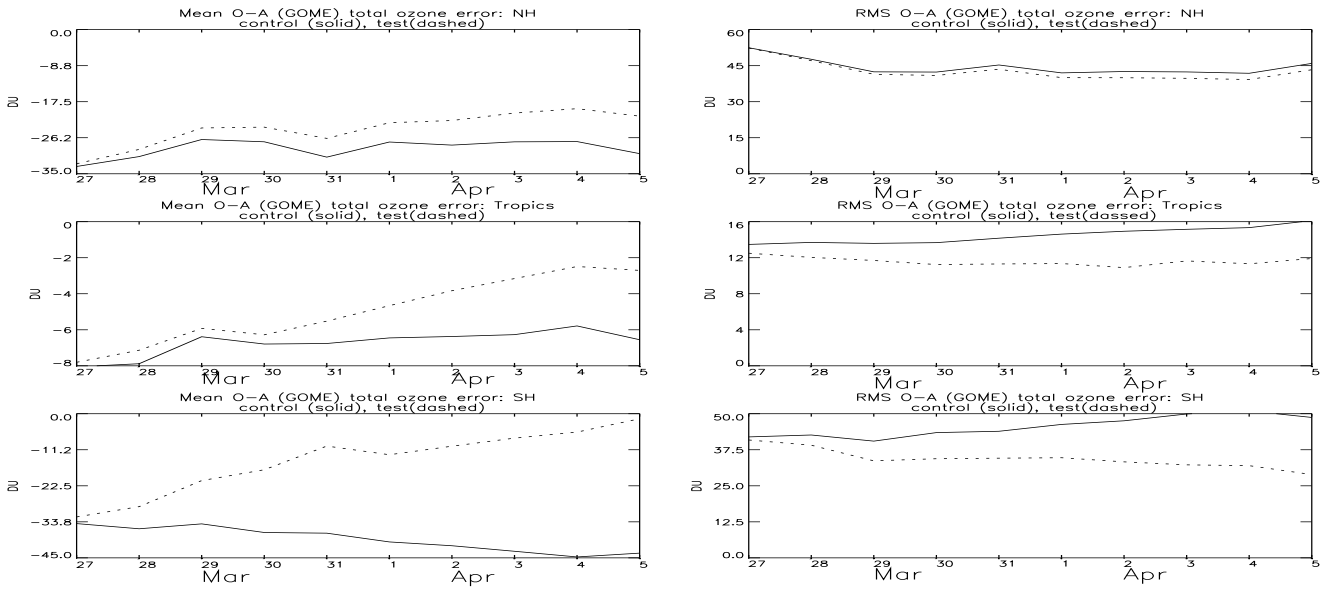

Figure 7: Mean and RMS GOME minus model (O-A) total ozone errors. Mean errors are on the left and RMS errors are on the right. Regions are northern hemisphere (30^o-90^oN) (top panels); tropics 30^oN-30^oS) (middle panels) and southern hemisphere (30^o-90^oS) (bottom panels). The results for the control run are plotted as solid lines, and those for the test run as dotted lines. Units: DU.

TOMS and GOME datasets. For the trial period TOMS total ozone exceeds GOME values by around 18-20 DU in the southern hemisphere and 6-10 DU in the northern hemisphere. This is consistent with Corlett and Monks (2001), who compared TOMS and GOME data for 1996-1999 and showed that TOMS total ozone consistently exceeds GOME total ozone in the southern hemisphere, by around 5 DU at low and middle latitudes rising to around 35 DU at the South Pole. A similar difference is present in the northern hemisphere, but is smaller, around 10 DU. A previous study by Lambert et al (1999) validated TOMS and GOME data against ground-based measurements and indicated a systematic over-estimation of 5-10 % in TOMS total ozone at all southern latitudes. GOME data generally did not show a systematic bias and were within 2-4% of the ground-based data.

To conclude, in the northern hemisphere and tropics, where TOMS and GOME data are in reasonable agreement, ozone assimilation shows a clear positive impact on the ozone analysis. In the southern hemisphere, where the discrepancies are greater, ozone assimilation appears to bring a large positive impact if validating against GOME data, but a sizeable negative impact if validating against TOMS data. There is some evidence that TOMS total ozone is less accurate than GOME data in that region (Lambert et al, 1999), but other validation studies have been less damning of TOMS data in this region. This makes it harder to assess the quality of the ozone assimilation in the southern

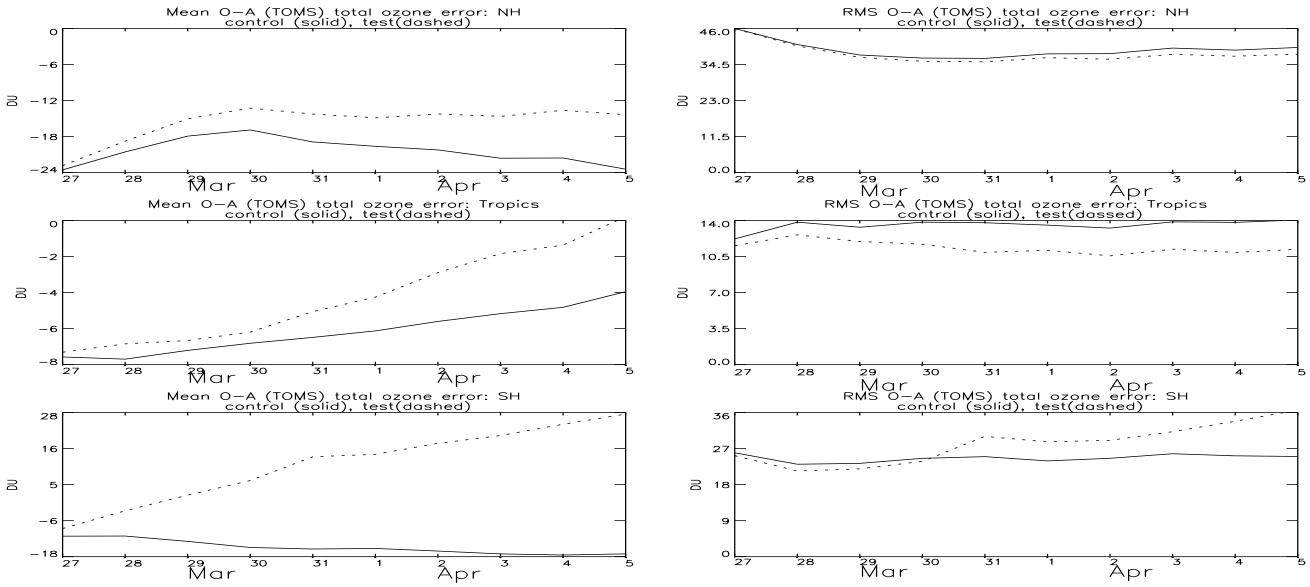

Figure 8: Like Figure 7, except errors compared to TOMS total ozone are shown.

hemisphere.

3.1.2 Verification against HALOE Ozone Profiles

Figure 9 compares trial and HALOE ozone profiles. For the trial period, no HALOE data were available in the northern middle and high latitudes and for other latitudes more sunrise than sunset data were available. Hence, Figure 9 shows HALOE sunrise data. There is good agreement between trial and HALOE ozone in the southern hemisphere, but in the tropics the trial values are too low near 10 hPa and too high above around 2 hPa. However, at these levels the model ozone mixing ratio will be strongly related to the trial ozone initial conditions, since the HIRS channel 9 data should only influence the ozone analysis in the lower stratosphere and upper troposphere. There, it is hard to see any difference between test and control run ozone profiles because the ozone mixing ratios there are much smaller than at the peak. Such differences are more clearly seen by plotting the mean difference between trial and HALOE ozone as a percentage of the HALOE profile (lower panel). In the upper troposphere and lower stratosphere the test run ozone is closer than the control run ozone to the HALOE profile (apart from between about 20 and 40 hPa), indicating a general improvement in analysed ozone when the ozone assimilation is switched on. The corresponding plot for the tropics shows much smaller differences between the control and test runs, probably because much fewer HIRS data are used in this region.

It should be pointed out that at levels near the tropopause the accuracy of the HALOE retrievals can become very poor if high amounts of aerosol are present (eg Bhatt et al, 1999). This could explain the high percentage differences between trial and HALOE ozone at these levels.

3.2 Impact on Analysed and Forecast Temperature

A claimed benefit of ozone assimilation is that, if the ozone analysis is realistic, ozone perturbations in all HIRS channels (and not only channel 9) that are sensitive to ozone will be properly represented, and this could lead to a more accurate analysis of temperature and water vapour. To this end, analysed and forecast fields of temperature for the control

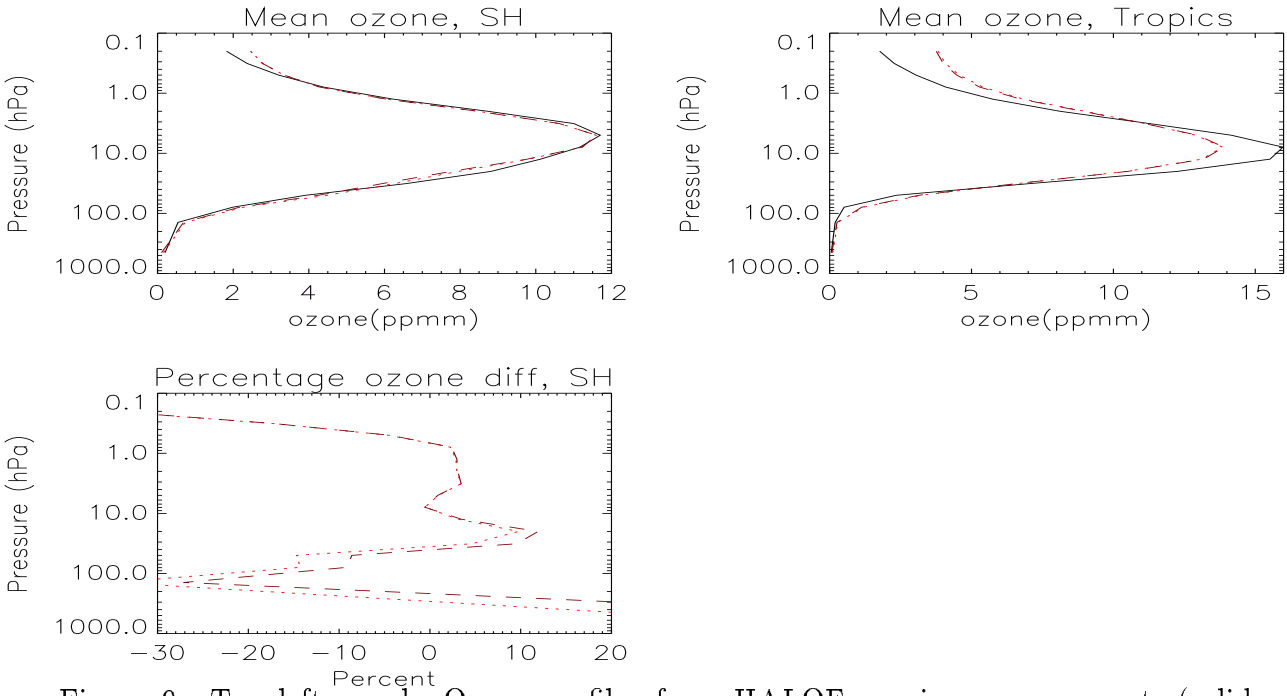

Figure 9: Top left panel: Ozone profiles from HALOE sunrise measurements (solid, black), the control run (dotted, red) and the test run (dashed, red) for the southern hemisphere (30°-90°S) Units: ppmm; Top right panel: Like top left, except data for the tropics (30°S-30°N) are shown; Bottom left panel: Percentage difference betwen HALOE and control run ozone (dotted, red) and between HALOE and test run ozone (dashed, red).

and test runs were compared. Figure 10 shows the mean and RMS differences between these fields and correlative sonde measurements in the tropics. It can be seen that both mean and RMS analysis errors (top panel) are reduced around the 400 - 600 hPa range when ozone is included, whilst for the forecast fields this reduction in the errors extends over a broader range, from around 900 to 200 hPa.

It should be pointed out that in the control run a rather poor estimate of ozone background ozone is being used in the forward model calculations of HIRS radiances, viz, an annual global mean reference profile. Accordingly, since HIRS channel 9 also has a strong sensitivity to temperature, it is very possible that the effect of this is to degrade the temperature analysis. To investigate this further another trial was run which was similar to the control run except that no HIRS channel 9 radiances were included at all (this is what is done operationally). The verification of the analysis and forecasts for this run are shown as blue lines in Figure 10. It can be seen that the difference between these errors and corresponding errors from test run are negligible. Thus, we conclude that the addition of a Stage 1 ozone assimilation would probably have a neutral impact on operational temperature analyses.

4 Future Developments

In Stage 2 of this work, the following further refinements to the assimilation system will be added.

- *Improved ozone background error covariances*: Currently, the ozone background error covariances used are based on data supplied by ECMWF. However, these data describe errors in the ECMWF forecast model, which may be different from

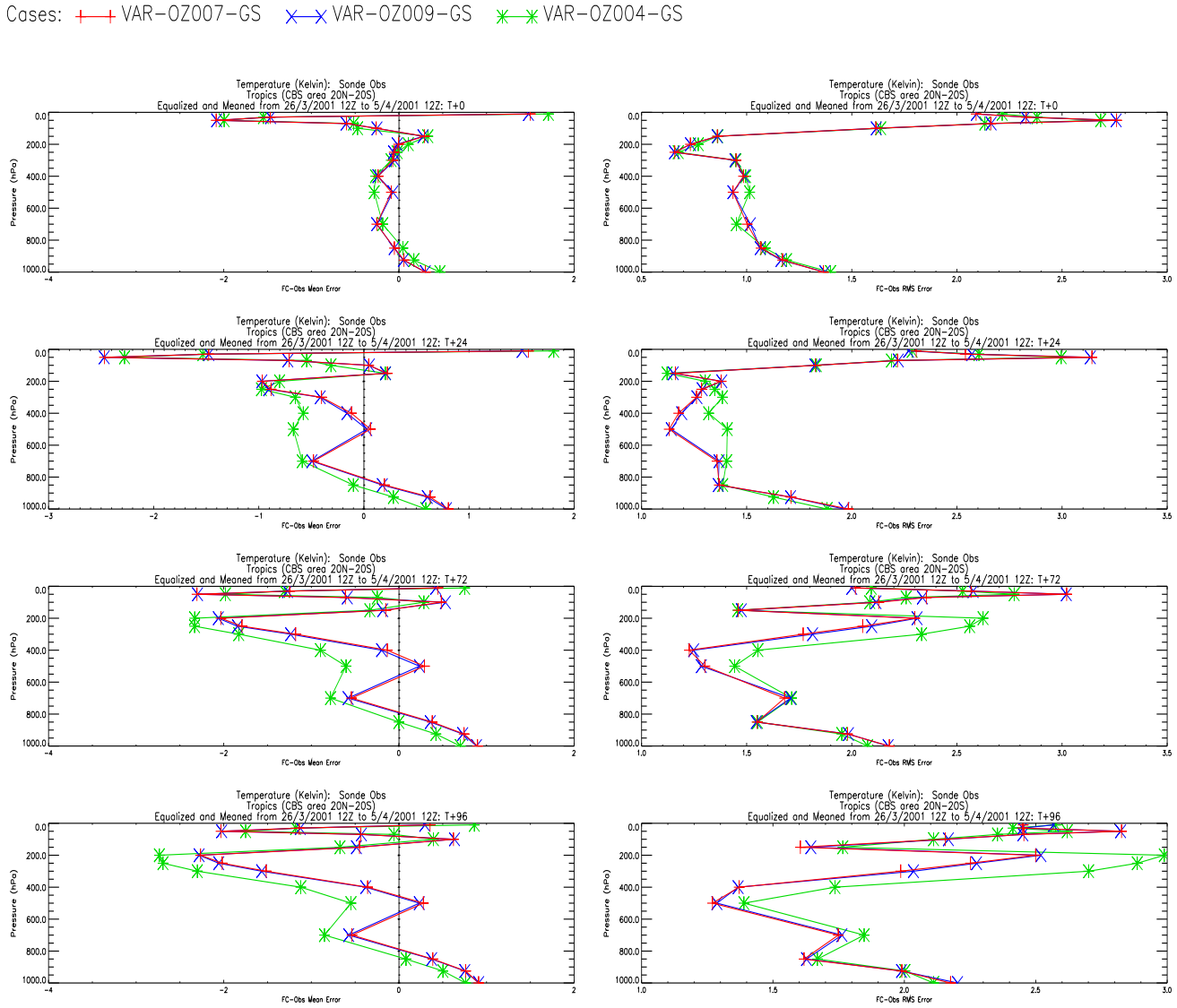

Figure 10: Verification of temperature against sonde data for the control run (VAR_OZ004-GS, green line), the test run (VAR_OZ007-GS, red line) and the control run with no HIRS channel 9 data included ((VAR_OZ009-GS, blue line: analysis (top panel), T24 forecast (2nd top panel), T72 forecast (2nd bottom panel), T96 forecast (bottom panel). Mean errors are on the left and rms errors on the right.

errors in the UM. In addition, these data may have been tuned to reduce analysis errors in the ECMWF system, but it does not follow that similar tuning is required for the Met Office ozone analysis. Thus, it is critical that background errors be calculated from UM statistics, rather than imported from another model system. Accordingly, statistics from planned month-long assimilation trials will be used to recalculate ozone background error covariances using the NMC method (Parrish and Derber, 1992).

- *Assimilate ozone observations from the SBUV instrument*: These observations will provide much more information about the vertical structure of the stratospheric ozone field than HIRS 9 data, which provide information only on the lower stratospheric / upper tropospheric ozone field. Thus, the large differences between tropical HALOE and analysed ozone in the middle stratosphere (Figure 9) may be reduced.

- *Parametrization of chemical ozone loss and production*: The background estimate of ozone can be greatly improved by including a parametrization of the chemical ozone changes which are very important in the middle and upper stratosphere. The Cariolle scheme (Cariolle and Deque, 1986) provides an efficient and reasonably realistic way of parametrizing the photochemical sources and sinks of ozone. In addition, the so-called 'cold tracer' scheme (Hadjinicolaou et al, 1997) will be added to represent ozone destruction due to heterogeneous chemistry associated with Polar Stratospheric Clouds.

- *Move system to UM5*: It is planned that the model used in the operational stratospheric assimilation will change to New Dynamics (UM5) in January 2003. The ozone assimilation system will also run on this system.

- *Include feedback to radiation*: When the above changes have been made, and the ozone analysis appears to be reasonably accurate, the feedback between ozone and radiation will be included by inputting analysed ozone, rather than climatological values, to the UM radiation scheme.

- *Change the ozone background error covariances to include correlations with other analysis variables*: This may lead to improved analyses of both ozone and wind, particularly in the upper troposphere and lower stratosphere.

The Stage 2 system may eventually be used operationally if it can be demonstrated that it has a positive impact on numerical weather forecasts. if this is the case, then it would be extended to include future model and observation developments (eg 4D-Var, assimilation of data from future satellite missions such as the Atmospheric Infrared Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI)).

In addition, the ozone assimilation scheme has also been used in an Observation System Simulation Experiment (OSSE) to assess the merit of stratospheric ozone and wind measurements made by the planned Stratospheric Wind Interferometer for Transport studies (SWIFT). The scheme used is like the Stage 1 scheme, except that it also includes the Cariolle chemistry parametrization. In future, ozone data from the Envisat satellite will be assimilated. It is likely that the Stage 2 system will be used for such experiments.

5 Conclusions

A simplified ozone assimilation scheme has been developed and has been trialled for 10 days using HIRS data. The results indicate that including ozone assimilation leads to a better analysis of total ozone in the northern hemisphere and tropics. The impact of assimilating ozone is even greater in the southern hemisphere, chiefly because more of the HIRS data are included the assimilation here than in other regions. Compared to GOME data, total ozone biases here are reduced by around 45 DU when the ozone assimilation is switched on. However, a similar comparison with TOMS data showed an increase in the O-A bias when ozone assimilation is switched on. It is possible that this difference is due to errors in the TOMS data in the southern hemisphere (Lambert et al, 1999). Furthermore, a comparison with HALOE data suggests that the introduction of ozone assimilation in general improves the estimated ozone profile. Such an improvement is restricted to the upper troposphere and lower stratosphere.

A verification of temperature against sonde data showed that using HIRS channel 9 data with the ozone assimilation scheme switched off leads to a degradation of analysed

and forecast temperature. This is not surprising, since in this case the ozone used in the HIRS forward model calculations is a fixed, global and annual mean profile. When compared against a run similar to above but with HIRS channel 9 data omitted, it was shown that the inclusion of ozone assimilation only has a neutral impact on analysed and forecast temperature.

The trials show that the existing ozone assimilation scheme performs satisfactorily, and that the analysed ozone fields (from the test run) are generally closer to correlative measurements than are fields that are simply advected by the mode winds (the control run). This means that the project can now proceed to Stage 2, and the improvements listed in Section 4 can be added.

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Appendix: Technical details of Changes required for ozone assimilation

The background ozone field is calculated in the UM using the tracer transport equation. This field has STASH code 61 (ozone tracer) and is passed between UM, OPS and 3D-Var systems. Ozone (STASH code 60) is currently read from an ancillary file (based on the Li and Shine climatology) and is only used in the UM radiation code. Ultimately, the code will be changed so that the radiation code uses asimilated rather than climatological ozone as an input.

OPS

- Ozone was included as an observation subtype in the ATOVSRad part of the code.
- BackErrCreate was extended so that ozone background error covariances could be added to BackErr file if required. Currently, these covariances are based on ECMWF data and are read in from a file. This is done via the line

```
export OPS_COVOZONE = /u/m11/data1/t11jk/ozone_cov/latest/cov_o3_16L.dat
```

- The ozone background error covariances were also included in the background error file in the $OPSDIR/namelists/ATOVS_coeffs_gs directory. These covariances are used in quality control (via a 1D-Var retrieval) of the ATOVS radiances.
- ATOVS bias corrections were recalculated with HIRS channel 9 included (operationally, this channel is omitted). Ozone STASH codes (61 for model level data and 16226 for pressure level data) need to be added to Extract and Process task namelists.

VAR

- The inclusion of ozone within the assimilation scheme is controlled by a namelist variable. To turn ozone assimilation on, one must specify:

```
export VAR_OZO_ASSIM = true
```

- One must use a covariance file which contains ozone covariances, eg

```
export VAR_COVACC=/u/m11/data1/t11jk/var/run/Var_Strat/COV_ACC.Acc_JunDec.IV
```

  Alternatively, such a file can be created by running a CovAccStats job on varui, with

```
export VAR_OZO_ASSIM = true
export VAR_COVOZONE=/u/m11/data1/t11jk/ozone_cov/latest/cov_o3_40L.dat
```

  specified in the job environment (see, for example, job VAMBD)

- Current trials have assumed that the horizontal ozone covariances are Gaussian with a length scale of 600 km. For older versions of Var (prior to Stable 18/1.xx), this means the following has to be placed in Var_TransformsNL namelist:

```
hShapeDefaultOzone=2,
hScaleDefaultOzone=0.094,
```

- Var_Grid and PPX_ref have to alter to account for the UM dump now containing the ozone tracer. These are available on the T3EB at

```
/u/m11/home/user1/t11jk/var/namelists/VarGrid_gs_9673_40/1.1
/u/m11/home/user1/t11jk/var/namelists/Var_PPXref
```

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